Implementation of a Technology Impact Forecast Technique on a Civil Tiltrotor*

Dimitri N. Mavris **Andrew P. Baker** **Daniel P. Schrage**

Aerospace Systems Design Laboratory (ASDL)
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA

Abstract

The methodology presented in this paper is concerned with the ability to make informed decisions early in the design time line in order to provide a feasible, viable and robust system to the customer. Increasingly, the issues of affordability, uncertainty in design and technology impact assessment are shaping the modern design environment. Current methodologies and techniques are not able to properly handle these issues. The research presented here builds on the authors' previous work which described an appropriate probabilistic design environment that allows for design in the presence of uncertainty as well as the infusion and assessment of new technologies. This environment is an essential part of a design methodology referred to as the Technology Identification, Evaluation and Selection (TIES) method. The objective of this research is to provide a comprehensive, structured, and robust methodology for decision making in the early phases of rotorcraft design. In this paper the authors will present a brief summary of the probabilistic design environment and introduce the steps that encompass the TIES methodology. The majority of the paper will be devoted to applying the Technology Impact Forecasting portion of this method to NASA's Short Haul Civil Tiltrotor.

Introduction

The modern design environment is a complex formulation directed towards providing a technically feasible, economically viable, robust solution to a customer's requirements. Traditionally, decisions are made early in the design time line which lock-in committed cost and lock-out design freedom at a time when knowledge about the design is limited.[1] This has led to a variety of concepts that attempt to provide design guidance to ensure system success. The two concepts that appear to have staying power, in this regard, are Design for Affordability and Integrated Product and Process Development (IPPD) which emphasize the life-cycle approach to design and which call for the shift of knowledge to the early design stages to reverse the aforementioned trends. Forecasting, with a high probability of success, the economic viability of the system in the early design stages now appears to be the key driving indicator of success. This issue of forecasting in design is directly linked to the ability of the designer to make informed decisions in the early design stages. Yet, the decisions made in the modern design environment increasingly involve choosing new technologies or combinations of new technologies that will ensure system success.

Traditional rotorcraft multidisciplinary design and analysis approaches are based on current engineering standards and practices as well as historical databases that limit the evaluation of non-evolutionary designs. Therefore, assessing the system attributes of a rotorcraft due to the infusion of an innovative technology and/or radical change in capability is difficult. The improvement or degradation caused by a new technology is often posed in the form of changes to appropriate discipline metrics. Rarely does the effect of a new technology uniquely link elementary design variables to system responses especially at the conceptual design level. Furthermore, the exact technology is often unknown and the only information provided is the constraint or objective that is being violated. Therefore, any new approach must provide a means to link discipline metrics to system responses to enable proper generic modeling of new technologies. What is needed is the ability to infuse new "breakthrough" technologies into the design process and evaluate their impact in terms of benefit, cost, and risk even before the time and expense of developing and maturing the technology is complete.

Furthermore, the push to Design for Affordability suggests a paradigm shift in which the design and evaluation of a system is no longer dictated solely by

---

* Presented at the American Helicopter Society 55th Annual Forum, Montreal, Quebec, Canada, May 25 - 27, 1999.

mission capability requirements. Instead, it is a robust design that balances mission capability with other system effectiveness attributes while keeping cost under close attention. This paradigm shift requires the designer to extend the deterministic, performance based design methods to account for disciplinary, economic, and technological uncertainty, and the presence of uncertainty demands a probabilistic approach.

In Reference 2, the authors described in detail the need and notion for an appropriate probabilistic design environment that allows for design in the presence of uncertainty as well as the infusion and assessment of new technologies. This environment is an essential part of a design methodology referred to as the Technology Identification, Evaluation and Selection (TIES) method developed at Georgia Tech.

In this paper the authors will present a brief summary of the probabilistic design environment and introduce the steps that encompass the TIES methodology. The majority of the paper will be devoted to applying the Technology Impact Forecasting portion of this method to NASA's Short Haul Civil Tiltrotor (SHCT). The failure or success of this vehicle will depend heavily on its affordability and represents an ideal platform for forecasting the impact of infused technologies. The research will be carried out utilizing appropriate metrics and technologies identified in the Department of Defense's Technology Development Approach as well as those identified at the recently convened 1st Joint Future Rotorcraft Requirements / Technologies / Programs Conference.

Technology Identification, Evaluation and Selection (TIES)

The seven step process known as TIES provides the decision maker/designer with the ability to easily assess and balance the impact of various technologies in the absence of sophisticated, time-consuming mathematical formulations. The method also provides a framework where technically feasible alternatives can be identified with accuracy and speed. This goal is achieved through the use of various probabilistic methods, such as Response Surface Methodology, Monte Carlo Simulations and Fast Probability Integration (FPI)[3]. Formalized techniques, borrowed from other scientific and engineering fields, are utilized to identify alternative concepts and aid in the decision making process. These techniques include Morphological Matrices[4], Pugh Evaluation Matrices[5], and Multi-Attribute Decision Making[6] methods. Through the implementation of each step, the best alternative for a given evaluation metric/criterion can be identified and assessed subjectively or objectively.

The TIES method (Figure 1) contains seven steps for implementation[7]. These steps are:

1. Problem Definition: Once the need for a new product is established, the designer must translate the qualitative needs and requirements of the customer into system product and process parameters. This process is facilitated through brainstorming techniques such as the Quality Function Deployment (QFD)[8] method. These techniques assist in defining the problem in terms of objectives, constraints and evaluation criteria. These system level metrics are used in subsequent steps to formalize the decision making process (Figure 1). For more information on the QFD technique, the reader is referred to Reference 9.

2. Baseline and Alternative Concepts Identification: As shown in Figure 1, the Pugh Matrix requires the identification of alternative concepts that are compared to yield the best alternative. The identification of these alternative concepts is facilitated through the use of the Morphological Matrix. This matrix provides an orderly decomposition of the system into subsystems or attributes that are subsequently combined to create alternative concepts. In this way, no combination of subsystems or attributes is overlooked in providing the best solution to a customer's requirements. The feasibility investigation commences with the identification of a baseline vehicle that most often identifies the present-day technology level.

3. Modeling and Simulation: A modeling and simulation environment is needed to quantitatively assess the metrics being tracked for the concepts identified in the Morphological Matrix. To facilitate the evaluation of many design alternatives and support sensitivity studies, conceptual design is most often performed with the use of monolithic or legacy synthesis/sizing codes. The method described in this paper does not abandon the accumulated knowledge represented by these codes but modifies their use to incorporate them into a probabilistic design environment and facilitate the assessment of new technologies. In this regard, one must ensure compatibility between the analysis code and the problem as defined in Step 1. The synthesis/sizing codes are, by nature, multi-disciplinary tools. Only the level of fidelity in each disciplinary area remains

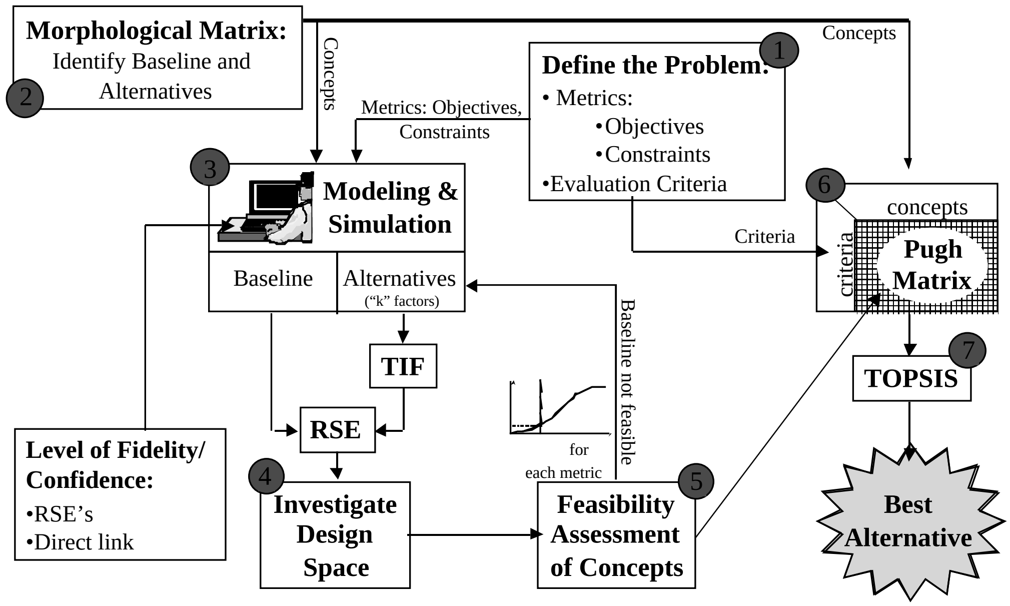

Figure 1: Technology Identification, Evaluation and Selection Methodology

an issue. When the chosen synthesis/sizing code is deficient, the appropriate analysis capability is introduced in the form of higher fidelity tools, physics-based analytical models, simulation capabilities, etc. These capabilities are provided by directly linking the analysis or more preferably, by introducing the analysis capability in the form of metamodels. For example, the emphasis on affordability would require the integration of a life-cycle cost model not normally found in synthesis/sizing codes. This process yields a preliminary design, vehicle-specific synthesis/sizing tool.

4. Design Space Exploration: This step provides for the establishment of the probabilistic design environment and the creation of the design space. The design space is created based on the design variables (and their ranges) defined in Step 1. In probabilistic design, the outcome sought is either a cumulative distribution function (CDF) or a probability density function (PDF) for each design objective or constraint. These distributions represent the outcomes of every possible combination of synthesized designs and are a representation of the feasible design space. The decision maker can now compare the CDF or PDF to a target value or required confidence level. The generation of these distributions entails the linking of the analysis codes with statistical techniques. Fox[10] lists three methods that incorporate such complex computer programs in a probabilistic systems design approach:

- Link a sophisticated design code directly to a random number generator such as a Monte Carlo Simulation to obtain the PDF or CDF of all desired code outcomes
- Approximate the sophisticated analysis code with a metamodel (e.g. Response Surface) and link it with a Monte Carlo Simulation
- Link the sophisticated analysis code with an approximation of the Monte Carlo Simulation

In this research the second and third methods are the most practical due to computational time considerations since ten thousand random simulations are typically needed for a reasonable CDF. In the third method, the Monte Carlo Simulation is approximated so as to yield results similar in fidelity while using only a handful of calculations. This approach is greatly facilitated through the use of a method referred to as the Fast Probability Integration technique. It is up to the designer's discretion to decide which method is most suitable. For a more detailed explanation of the various choices in this step, one is referred to Reference 2.

5. Determination of System Feasibility: Probability of Success: Once the target value for a specific metric is identified, concept feasibility is evaluated via the appropriate CDF by overlaying the target value. The CDF provides a plot of the metric value versus the probability of feasibility (success). The intersection of this target value with the CDF identifies the probability of success or confidence one has in

achieving the imposed target. The decision maker can then impose a confidence level which must be met in order to consider the metric effectively satisfied. This process indirectly addresses the amount of risk the decision maker is willing to absorb in the early stages of design. This process also facilitates the identification of active constraints (i.e. metrics which do not meet the imposed confidence level). If no constraints (either technical or economic) are active then the system is feasible and viable and the designer can proceed to the next step in the method. Relieving active constraints can be accomplished by relaxing the target value, relaxing the required confidence level or manipulating design variables within their ranges. When these techniques are ineffective, the infusion of new technologies is the only recourse.

Formulation of new technologies in terms of elementary variables does not lend itself to disciplinary or multidisciplinary technology assessment. Hence, the assessment of new technologies must be addressed through the metrics they affect. The solution is to model and define technology metrics for the new technologies as a delta with respect to current technology based on subjective experience. In practical terms, technology metric "k" factors are introduced into the analysis or sizing tool to infuse a hypothetical enhancement or degradation associated with the new technology. In effect, the "k" factors simulate the discontinuity in benefits or penalties associated with the addition of a new technology.

The cumulative distribution functions are now re-evaluated with the metric "k" factors as design variables. The CDF "shift to target" is illustrated in Figure 2. This figure shows the shifting of the design space caused by the infusion of the new technology as an increase in the P(feas) with the same constraint value overlaid. As previously discussed, the "k" factors are introduced to produce beneficial as well as degraded effects. The result in Figure 2 would be typical of the results for the objective or constraint at which the new technology is directed. However, new technologies cannot be assessed from a benefit viewpoint alone. The effect on other disciplinary metrics must be included to completely assess the impact on the entire system. The penalties to other metrics may dominate the benefit applied by degrading the performance of other metrics.

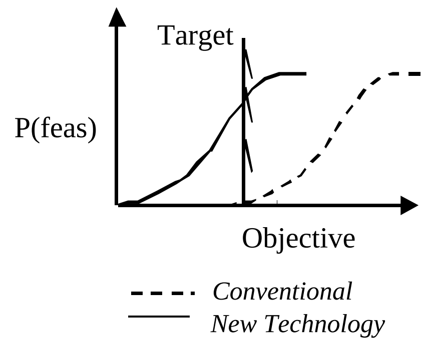

Figure 2: New Technology Improvement

This formulation is known as the Technology Impact Forecasting (TIF) environment and provides the means to assess technologies or combinations of technologies needed to overcome technical and economic barriers in the system design. It provides "k" factor levels needed to overcome a constraint without adversely affecting other metrics. An actual technology must be identified which can provide the "k" factor projections but it provides guidance for resource allocation and project development. Further details are given in Reference 2.

6. Population of the Pugh Evaluation Matrix: The Pugh Evaluation Matrix provides an organized technique for gathering the data required to choose a best alternative. It is populated with numerical values for the evaluation criteria identified in Step 1 (rows). This data is provided for each of the alternatives defined by the Morphological Matrix (columns). This data is derived from the feasibility assessment previously described with a fixed confidence level imposed by the decision maker. This process is repeated for each metric and concept. It should be noted that the Pugh Evaluation Matrix, as originally conceived, is aimed at decision making under subjective terms when numerical data was unavailable. The matrix is populated based on a subjective scale determined by experts in the system (e.g. Integrated Product Team). The same nomenclature is used in this research although its use is not strictly correct.

7. Best Alternative Concept Determination: The creation of the Pugh Matrix illustrates the complex multi-criteria decision making environment in which the best alternative is chosen. For the purpose of the TIES methodology, a Multiple Attribute Decision Making (MADM) technique known as Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is utilized. TOPSIS provides an indisputable preference order of the solutions obtained in the Pugh Matrix resulting in the best

alternative concept. This best alternative is established as described below:

- Nondimensionalize each criterion for a given alternative by the norm of the total outcome vector
- Establish relative importance for each criterion through subjective weightings
- Classify each criterion as a benefit or cost to the system
- Establish positive and negative ideal solution vector
- Determine Euclidean distance of each alternative relative to both the positive and negative ideal solution
- Rank alternative concepts based on closeness to positive ideal solution and distance from negative ideal solution

These rankings can change depending upon the level of confidence and criterion weightings assumed. Finally, the robustness of the best alternative can be evaluated with various techniques. One method developed in Reference 11 is the Robust Design Simulation.

Application of Method

A long smoldering fascination with the tiltrotor concept has finally burgeoned into the production of a military (V-22) and civilian (Bell 609) version. These successes will hopefully blossom into a civilian version in the 30 – 40 passenger range where the capabilities of such a unique vehicle can be best exploited. Undoubtedly, the affordability of such a vehicle will be a key to its success and the infusion of new technologies will play a significant role in overcoming technical barriers and reducing costs. Therefore, this section will illustrate parts of the TIES method for NASA's Short Haul Civil Tiltrotor. In particular, the application of steps 1-5 will be demonstrated with emphasis applied to the Technology Impact Forecasting approach.

1. Problem Definition: The baseline vehicle for this study is NASA's Short Haul Civil Tiltrotor (4/95 Baseline). The design mission consists of a 600 nm design range at a cruise speed of 350 knots with a 50 nm and 45 minute reserve mission[12] (1962 U.S. STA ATM Cond - Zero). The original set of design variables (both control and economic/noise) is shown in Table 1. Note that all results presented are normalized with respect to the baseline values except where specifically mentioned.

Table 1: Design & Economic Variables Considered

Maneuver Load Factor
Wing Aspect Ratio
Wing Thickness/Chord Ratio (tip/root)
Wing Loading
Wing quarter chord sweep (degree)
Horizontal Tail Thickness/Chord Ratio
Horizontal Tail Volume Coefficient
Vertical Tail Thickness/Chord Ratio
Vertical Tail Volume Coefficient
Tip speed
Propeller Diameter
Thrust coefficient /solidity
Rotor Thickness/Chord Ratio
Engine Scale Factor
Economic Range
Production Quantity
Utilization
Manufacturer Return on Investment
Airline Return on Investment
Fuel Cost
Load Factor
Hull Insurance Rate
Learning curve

The goal is to create a design space examination (in the form of a cumulative distribution function), through the use of Response Surface Equations and Monte Carlo Simulations, which is defined by the choice of these design variables and their ranges. Due to the large number of design variables and limitations in the statistical computer packages used to create the probabilistic design environment, the Pareto principle is used to narrow the choice of design variables. This principle states that commonly a small subset, 20%, of the input variables is responsible for most, 80%, of the variability of a desired response. In the context of Response Surface Methodology, this task is completed using an effects screening test also known as an analysis of variance. Effects screening is used to determine the sensitivity of a response to various inputs and screen out those inputs that do not contribute significantly to the variability in the response. These inputs are not lost but set to their most likely values. After the screening test, the variables shown in Table 2 are retained as the most influential and Table 3 shows the objectives and constraints which are tracked in this study.

The ranges shown in Table 2 define the boundaries of the design space that is created through the implementation of a Design of Experiment[13] (DoE). The DoE provides a statistically efficient combination of experiments (simulations) necessary to collect the needed response data (Objective and Constraint values). The DoE and corresponding response data provide the means to create a Response Surface Equation (RSE) through a least squares fit.

Table 2: Design Variables & Ranges (Normalized)

	Minimum	Baseline	Maximum
Wing Aspect Ratio	0.78	1.00	1.04
Wing Loading (lb/sq ft)	0.92	1.00	1.08
Tip speed (fps)	0.93	1.00	1.07
Propeller Diameter (ft)	0.93	1.00	1.10
Thrust coefficient /solidity	0.87	1.00	1.05
Economic range (nm)	1.00	1.00	3.00
Eng Scale Factor (MCP,Deg F)	0.99	1.00	1.07
Production quantity	0.80	1.00	1.20
Utilization (hrs/yr)	0.80	1.00	1.40
Manufacturer ROI (%)	0.67	1.00	1.33
Airline ROI (%)	0.50	1.00	1.50
Fuel cost ($/gal)	0.77	1.00	1.41
Load factor	0.92	1.00	1.46
Hull Insurance Rate (%)	0.20	1.00	2.00
Learning curve	0.98	1.00	1.10

Table 3: Objectives & Constraints

Gross Weight
Empty Weight
Installed Power
L/D*Propulsive Efficiency
Disk Loading
Wing Area
500 Ft Sideline Noise
Direct Operating Cost (DOC)
Direct Operating Cost+Interest (DOC+I)
Required Average Yield Per Revenue Passenger Mile ($ / RPM)
Price / Installed Power

The RSE provides a relationship for the objectives and constraints as a function of the design variables.

2. Baseline and Alternative Concepts Identification: A Morphological Matrix created for the SHCT is shown in Table 4. The shaded circles indicate the baseline vehicle for this research with a certain level of technologies applied. When any shaded oval is moved, this represents another alternative concept and may reflect the infusion of new technologies. These alternative concepts would populate the Pugh Matrix in Steps 6 and 7. Since these steps are not emphasized in this application, the baseline alternative is the only one analyzed.

Table 4: Morphological Matrix

Alternatives / Characteristics	1	2	3	4
Configuration				
Wing	High Mount	Mid Mount		
Tail	T-Tail	Fuselage-Mounted	H-Tail	
Fuselage	Circular	Non-Circular		
Pilot Visibilty	Synthetic Vision	Conventional		
Seating	3-Abreast	4-Abreast		
Mission				
Range (nm)	400	500	600	
Passengers	30	35	40	
Cruise Speed	300	325	350	375
Rotor				
Configuration	Conventional	VDTR		
Blades/Rotor	3	4	5	
Hub	Articulated	Bearingless	Hingeless	
Propulsion				
Engine	Tilting	Non-Tilting		
Speed	Fixed	Variable		
Power	Normal	Derated		
Structural				
Materials	Aluminum	Composites	Combination	

3. Modeling and Simulation: In order to create the environment needed to analyze the various concepts, the synthesis/sizing code VASCOMP II[14] was enhanced. This enhancement provided the ability to properly model the baseline vehicle. In order to address economic concerns, the Tiltrotor Aircraft Life-Cycle Cost Analysis (TRALCCA) code was developed using NASA Ames' ALCCA as a framework. Newly developed modules for research, development, testing and evaluation (RDT&E) and production cost were incorporated and this analysis capability was integrated into VASCOMP II including the passing of all relevant outputs (weights, block speed, block time). This combined code allows economic analysis for the design mission and/or subsequent economic missions. Capabilities include manufacturer and airline cash flows, operating costs (DOC, DOC+I), required average yield per revenue passenger mile($/RPM), acquisition cost, internal rate of return, break-even units, etc. The tracking of all objectives and constraints is done using this combined analysis code.

4. Design Space Exploration: In this study, the results shown are created using the Response Surface Methodology and Monte Carlo Simulation option. RSEs are created for all objectives/constraints as a function of the design variables for the feasibility assessment. The examination of the design space takes on a very graphical format in this methodology which gives the designer / decision maker a powerful tool for playing "what if" games with the design space. As previously mentioned, the design space is represented by the CDF generated for each system metric. Through the use of inexpensive commercial-off-the-shelf software, including the statistical computer package, JMP[15] and the Monte Carlo Simulator, Crystal Ball[16.]; the CDFs are easily created. The JMP package also provides interactive visualizations of the design space in the form of prediction profiles and contour plots. Further information on this process is available in Reference 2.

5. Determination of System Feasibility: Probability of Success: The cumulative distribution functions representing the design space are shown in Figure 3 with the baseline values indicted as 1.0 on the abscissa. Target values can be applied to these plots to identify the constraint that provides the most difficulty. For example, say the designer wanted to limit the gross weight to 95% of the baseline value or the installed power to 80% of the baseline value. Figure 3a and Figure 3b indicate there is less than a

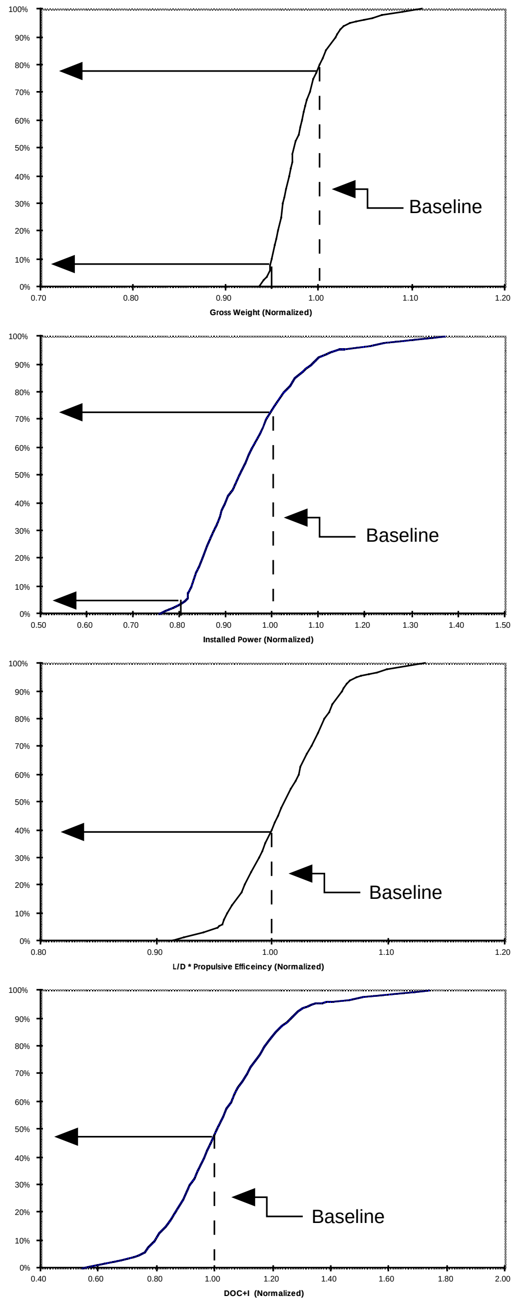

Figure 3: Design Space Representation With No Technologies Applied: Uniform Distribution Over Design Variable Ranges

10% probability of success of attaining these targets with current technology. Thus, technologies that affect weight and engine power would become possible areas for technology infusion. Considering the influence of affordability on a civil tiltrotor, one might look at an economic metric such as DOC+I. This metric includes direct operating costs such as fuel cost, crew cost and maintenance cost as well as the cost of ownership (depreciation, hull insurance, financing). Figure 3d indicates that the probability of feasibility for the baseline is less then 50%. Thus, any decrease in DOC+I, which is likely needed for system viability, is improbable in the current design space and requires the infusion of new technologies.

Another way to visualize the design space is through carpet plots in the form of contour plots provided in JMP. An example of this presentation is given in Figure 4 for the SHCT. This screen is interactive and has the power of the response surface equations behind it. It allows manipulation of design variables within the specified ranges and the placement of limits on design objectives. Although difficult to see in grayscale, the display is shaded with the appropriate color for the objective/ constraint that is being violated. By using the slide bars for the design variables, the design space can be searched, in real time, to determine if the constraints can be satisfied by manipulation of the design variables. Feasible space in the contour plots is indicated by white (or unshaded) space. If there is no feasible space then various remedies including technology infusion can be pursued. The slide bars for the objectives / constraints are useful in depicting the magnitude of the violation. When the dots fall within the shaded region the objective is violated and the distance to the unshaded

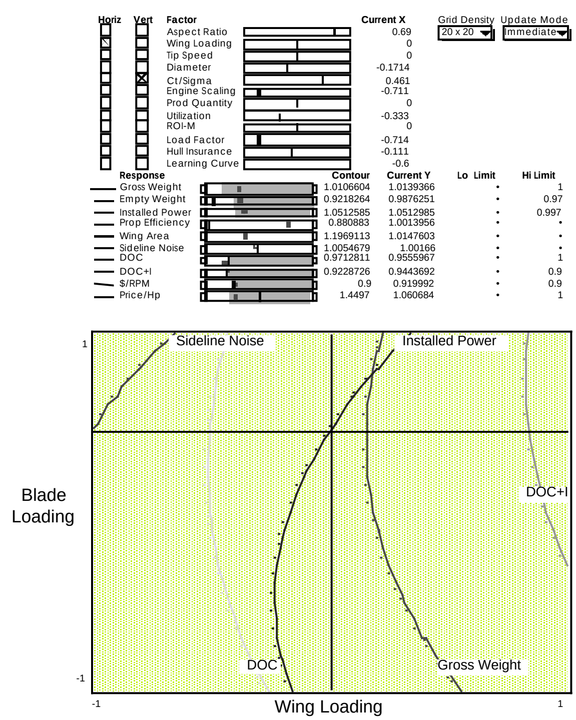

Figure 4: Visualization of Design Space

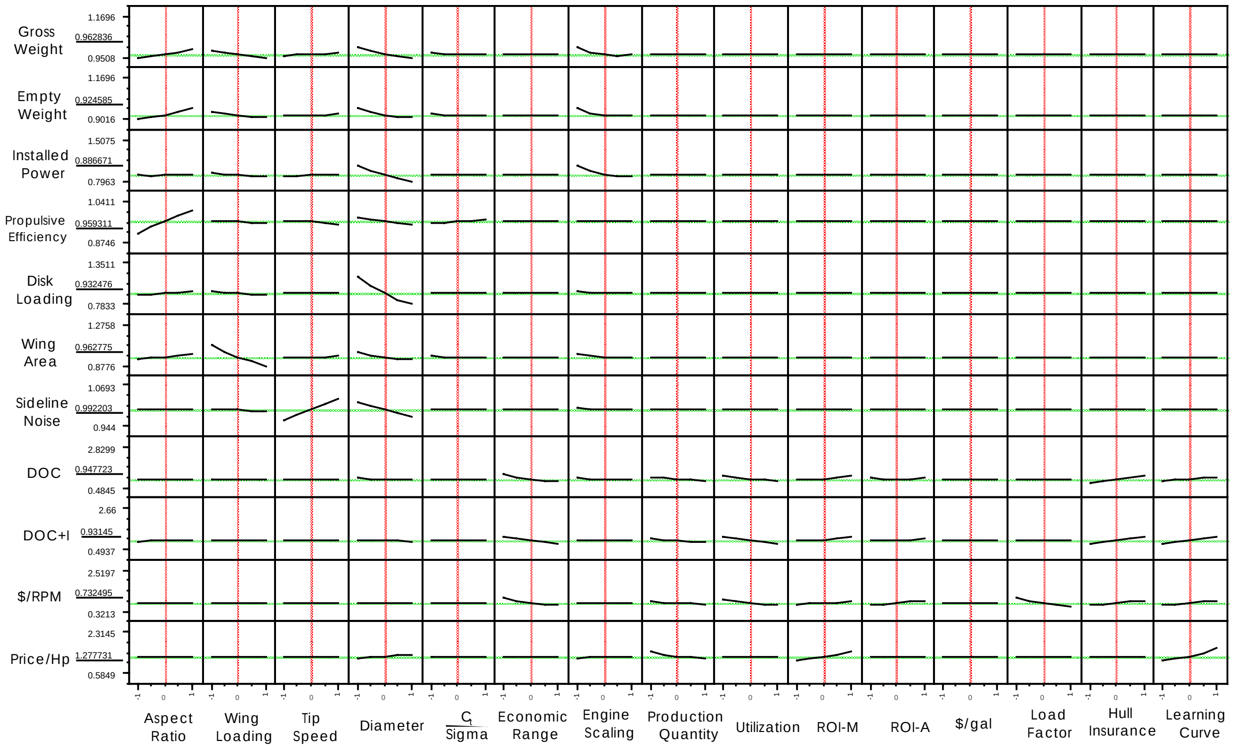

Figure 5: Feasible Design Space Examination

region indicates the magnitude of the violation. The contour lines shown in Figure 4 are for illustrative purposes only. The placement of the contour lines is controlled by the designer and aids in performing sensitivity studies. Likewise, the dots accompanying the contour lines indicate the direction of increasing metric value. The design variables in this plot are presented on a scale from –1 to 1 which correspond to the low and high limits, respectively, of the range assigned to that variable.

In Figure 5, prediction profiles are presented which show the relationship between the objectives /constraints (ordinate) and the design variables (abscissa). This screen is also interactive. When the hairlines (light gray vertical lines) are moved to indicate the changing of a design variable value, the objectives/constraints are automatically updated through the RSE. Thus, one can investigate the design space by manipulation of the design variables to determine if an objective can be met. The slopes indicate the relative effect each variable has on the objectives. On a more practical note, this screen is often helpful as a debugging tool since trends can be verified and potential mistakes located. The design variables in this plot are again presented on a normalized scale.

Technology Impact Forecasting

Since the affordability of a 30-40 passenger tiltrotor will be a key driver in the vehicle's success, an example in this spirit is shown. The objective is to show a 10% improvement in an appropriate economic metric; direct operating cost plus interest (DOC+I). The technologies chosen for the impact assessment include a composite fuselage, contingency power and a futuristic engine (dubbed the smart, green engine). Although specific technologies are identified for this example, the TIF environment is created in the most generic manner. This generality allows for the implementation of other technologies or simply the identification of metric improvements that will provide the best solution. These metric improvements are then used to identify potential technologies or combinations of technologies. The technology metric "k" factors for this TIF environment are presented in Table 5. The ranges for each factor reflect both benefit and degradation with respect to the baseline or nominal metric value. This formulation ensures that technology modeling can handle both the primary benefit and secondary degradation of appropriate metrics. Table 6 provides the metric values used for the three technologies applied in the example.

Table 5: Technology Metric 'k' Factors

Technology "k" Factor	Low	High
k_Fuel Flow	0.8	1.1
k_Hover Efficiency	0.95	1.1
k_Propulsive Efficiency	0.95	1.1
k_Download	0.6	1.05
k_Contingency Power	1.119	1.31
k_Wing Drag	0.8	1.05
k_Nacelle Drag	0.8	1.05
k_Spinner Drag	0.8	1.05
k_Wing Weight	0.8	1.05
k_Fuselage Weight	0.7	1.05
k_Rotor Weight	0.8	1.1
k_Drive System Weight	0.9	1.1
k_Engine Weight	0.75	1.1
k_RDTE Cost	-0.1	0.2
k_Production Cost	-0.1	0.2
k_O&S Cost	-0.1	0.2

In this TIF environment, a relationship (RSE) is created between the objective/constraint and the metric "k" factors that simulate the "application" of a new technology. Once again, the prediction profiles shown in Figure 6 present a graphical means of exploring this new design space. The "k" factors are presented on a normalized scale. The slope of the relationship indicates the relative impact each metric improvement can have on the specific objective. Since this plot is interactive, "k" factors are manipulated to reflect the benefit or degradation associated with a specific technology and objective values are automatically updated. The application of a combination of technologies involves the simple addition of "k" factor effects from the proposed technologies.

Table 6: Three Technologies for Application

Contingency Power	Benefit/Degradation
k_Contingency Power	1.31
k_Engine Weight	0.03
k_O&S Cost	0.02
Composite Fuselage	
k_Fuselage Weight	0.8
k_Fuel Flow	0.995
k_RDTE Cost	0.02
k_Production Cost	0.05
k_O&S Cost	0.02
Smart Green Engine	
k_Fuel Flow	0.9
k_Engine Weight	0.7
k_RDTE Cost	-0.04
k_Production Cost	-0.03
k_O&S Cost	-0.03

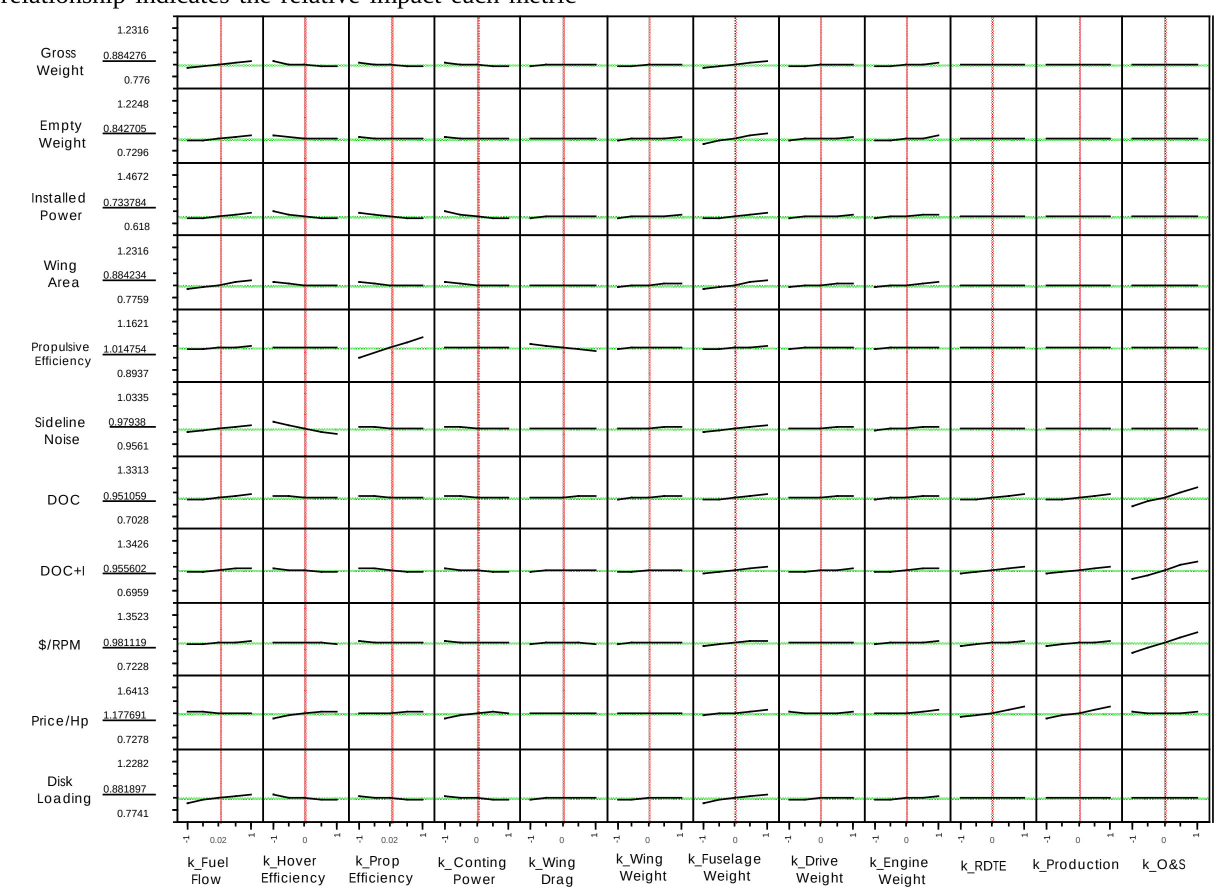

Figure 6: Technology Impact Forecasting Environment

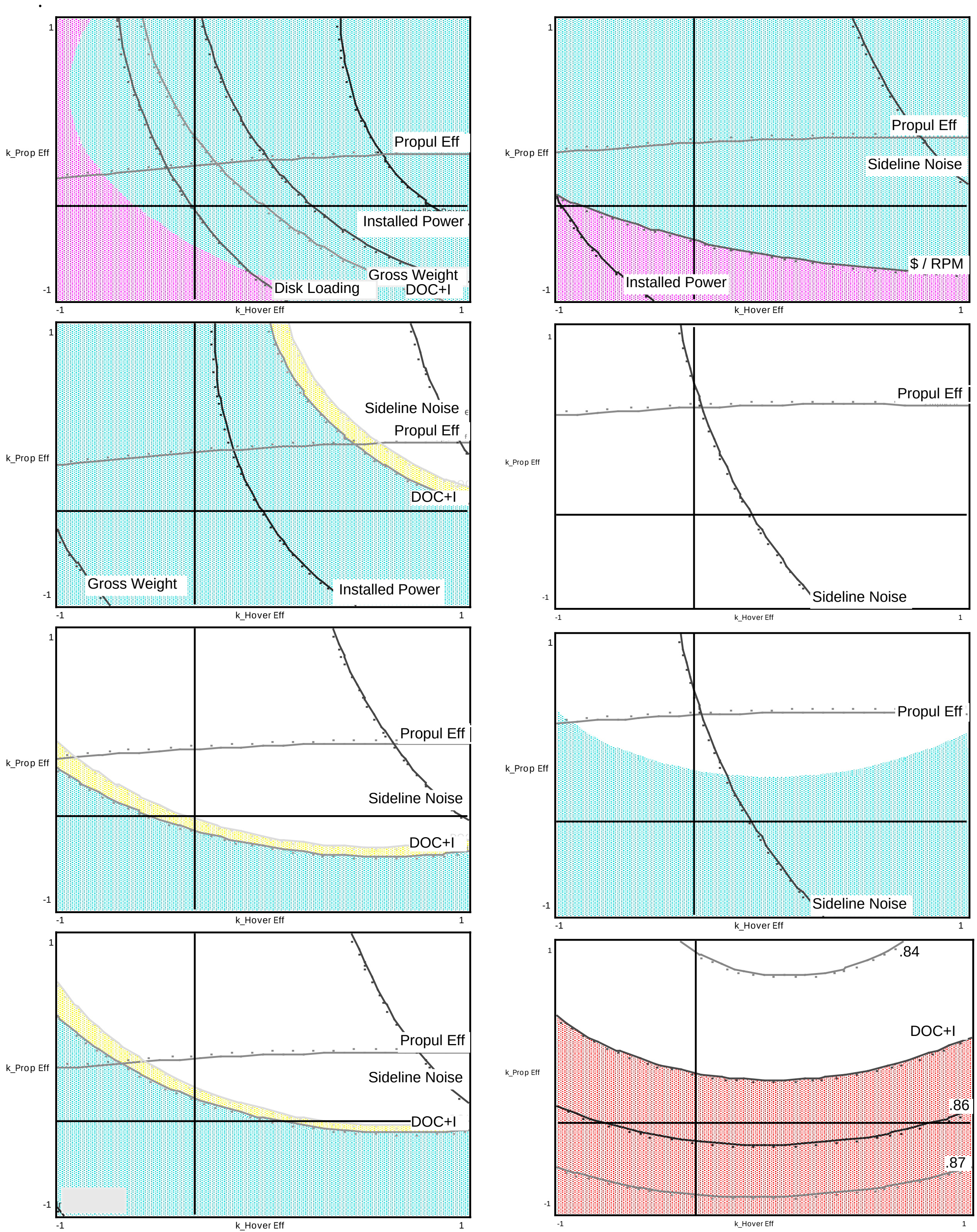

Figure 7: Technology Impact Forecasting

With the appropriate design environment established, the impact of the chosen technologies can be assessed. Figure 7 illustrates the progressive application of the new technologies at various levels and the subsequent impact on the proposed goal of improving the DOC+I. Figure 7a represents the original design space with no technologies applied and the imposed constraint on DOC+I. The original space is fully shaded indicating no viable solutions exist. The contour plots in this sequence are shown with the propulsive efficiency metric versus the hover efficiency metric. This presentation is not mandatory and any combination of metrics can be displayed (see Figure 4). Figure 7b illustrates the benefit associated with applying a composite fuselage. The resulting effect on the design space is indicated by the unshaded portion of the plot. However, the positioning of open space in this visualization of the system design space indicates that some improvement in hover efficiency and/or propulsive efficiency must exist. Either the propulsive efficiency or the hover efficiency must be improved for the DOC+I to be decreased by 10%.

Figure 7c shows the additional benefit derived from applying contingency power to the vehicle. The design space has opened considerably and indicates there is no need for new technologies beyond the composite fuselage and contingency power. However, these technologies are applied from a purely beneficial point of view. The next two plots (Figure 7d & Figure 7e) show the application of secondary effects to the vehicle. First, an engine weight penalty is applied and then the impact on RDT&E, operation and support (O&S) and production costs are applied. As each penalty is applied the design space closes until there is no viable space remaining. Thus, even with the application of two new technologies, the improvement sought in DOC+I is not reachable.

Searching through each combination of “k” factors as axes for the contour plots, the only combinations that provided a viable design space are those involving fuel flow. This indicates the need to consider a technology effecting the engine fuel flow rate. Figure 7f illustrates the application of the smart green engine with a dramatic opening of the design space. Thus the application of three technologies provides the desired improvement in DOC+I with no other technologies needed. However, suppose the projected improvement in O&S cost (see Table 6) is over-optimistic for the smart green engine. This environment allows the decision maker to determine

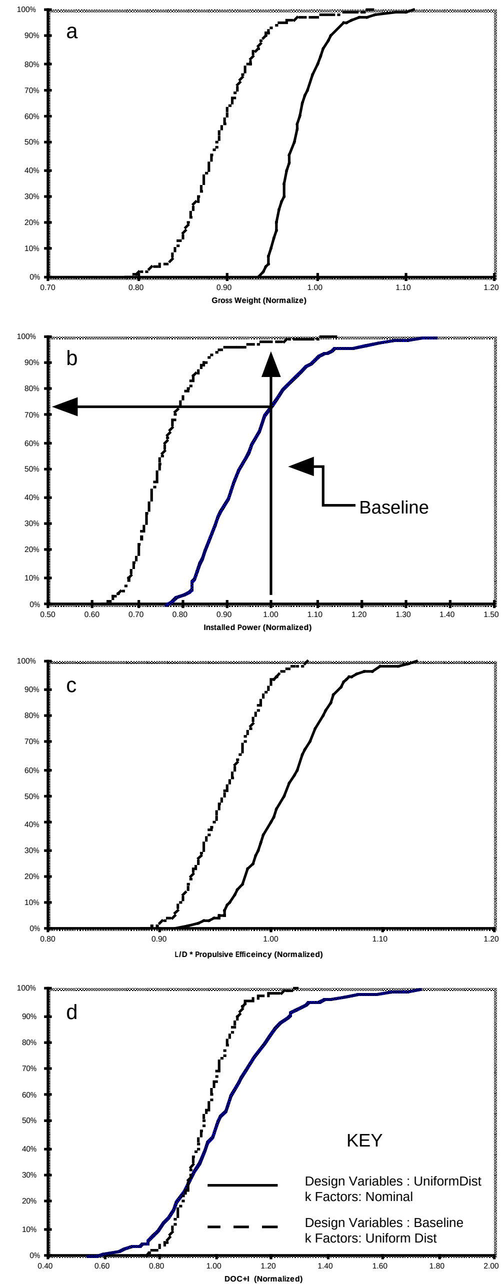

Figure 8: Identifying Constraints and Bounding The Problem

the increase in cost that can be tolerated while keeping a viable design space. This proposition was investigated and resulted in a 7.5% increase in O&S cost which could be absorbed and still ensure a large viable design space.

The final two plots investigate the possibility of improving the DOC+I beyond the original 10%. Figure 7g shows the design space with a 15% decrease in DOC+I imposed. There is still viable design space that indicates the 15% decrease in the goal is possible with this combination of technologies. Figure 7h shows multiple contours of DOC+I (in % improvement) illustrating the sensitivity of the design space to improvements in DOC+I.

The contour plots shown in Figure 7 provide an excellent illustration of how this environment can be used to efficiently search for combinations of technologies which meet imposed constraints. It should be emphasized that Figure 7 is not meant to provide “the” answer to a specific problem. It is meant to highlight the environment which allows the decision maker to assess the impact of any combination of technologies. The power and utility of the methodology are realized through visualizations such as contour plots.

Finally, in Figure 8 the influence of the new technologies (through application of the “k” factors) on the design space is examined through the cumulative distribution functions. In Figure 8, the solid line indicates the original design space with the “k” factors at their nominal values. This line represents a family of sized vehicles with current technologies applied. The dashed line represents only the baseline vehicle but with a uniform distribution applied to the “k” factors during the Monte Carlo Simulation. This formulation then bounds the problem. The baseline vehicle, with all technologies applied can do no better or worse than indicated by the tails of the distribution. Thus, if a target value is superimposed for a required constraint and it cannot meet the confidence level set by the decision maker then the technologies chosen will never meet the target. Different technologies or different combinations of technologies must be sought to overcome the “show-stopper”.

Concluding Remarks

The Technology Identification, Evaluation and Selection methodology is a seven step process which facilitates the making of informed decisions in the early design stages. The application of this method to NASA’s Short Haul Civil Tiltrotor has demonstrated the unique capability to assess the impact of new technologies. Through the use of inexpensive commercial statistical packages, the methodologies created and implemented under this research have provided the decision maker with tools beyond the state-of-the-art. The graphical nature of this method allows the conceptual designer and/or decision maker to analyze the feasibility and viability of a complex system as well the impact of new technologies from a benefit/cost point of view. Future work includes the creation and application of a resource allocation capability beyond what is currently included in this method.

Acknowledgments

The work presented in this paper is supported partially under Task 9.2.1 for the National Rotorcraft Technology Center (Contract No. NCC-2-945) and partially under a grant for the Office of Naval Research (Contract No. N00014-97-1-0783) to support the Affordability Measurement and Prediction Initiative. The authors would like to thank the Systems Analysis Branch at NASA Ames as well as Mr. Jimmy Tai, Ms. Elena Garcia and Ms. Michelle Kirby for their assistance.

References

1 Fabrycky, W.J., Blanchard, B.S., Life-Cycle Cost and Economic Analysis, Prentice-Hall Inc., Englewood Cliffs, New Jersey, 1991.

2 Mavris, D.N., Baker, A.P., Schrage, D.P., “Development of a Methodology for the Determination of Technical Feasibility and Viability of Affordable Rotorcraft Systems”, Proceedings of the54th Annual AHS Forum, Washington, D.C., May 20-22 ,1998.

3 Southwest Research Institute, FPI User’s and Theoretical Manual, San Antonio, TX, 1995.

4 Twiss, B.C., Forecasting for technologists and engineers: A practical guide for better decisions, Peter Peregrinus, Ltd., London, U.K. 1992.

5 Pugh, S., Creating Innovative Products Using Total Design, Addison-Wesley Publishing Co., Reading MA, 1996.

6 Hwang, C.R., Yoon, K., Lecture Notes on Economics and Mathematical Systems, Springer-Verlag Berlin Heidelberg, New York, 1981.

7 Mavris, D.N., Kirby, M.R., Qiu, S., “Technology Impact Forecastring for a High Speed Civil Transport”, SAE Paper 985547.

8 Kusiak, A. (Editor), Concurrent Engineering: Automation, Tools, and Techniques, John Wiley & Sons, Inc., 1993.

9 Kusiak, A. (ed.), Concurrent Engineering: Automation, Tools and Techniques, John Wiley & Sons, Inc., 1993.

10 Fox,E.P., “The Pratt & Whitney Probabilistic Design System”, 35th AIAA/ASME/ ASCE/

AHS/ASC Structures, Structural Dynamics, and Materials Conference, Hilton Head, SC, April 1994.

11 Mavris, D.N., Bandte, O., Schrage, D.P., "Application of Probabilistic Methods for the Determination of an Economically Robust HSCT Configuration", AIAA 96-4090.

12 Brender, S., Mark, H., Aguilera, F., "The Attributes of a Variable-Diameter Rotor System Applied to Civil Tiltrotor Aircraft", NASA University Consortium Grant NCC2-5174, 1996.

13 Montgomery, D.C., Design and Analysis of Experiments, John Wiley& Sons, 1991.

14 Schoen, A.H., Rosenstein, H., Stanzione, K., Wisniewski, J.S., User's Manual for VASCOMP II: The V/STOL Aircraft Sizing and Performance Computer Program, Version 1.15, Boeing Vertol Company, August 8 1995.

15 SAS Institute Inc., *JMP, Computer Program and Users Manual*, Cary, N.C., 1994.

16 Decisioneering, Inc., *Crystal Ball, Computer Program and Users Guide*, Denver, CO, 1993.